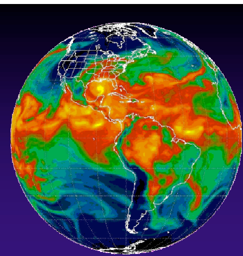
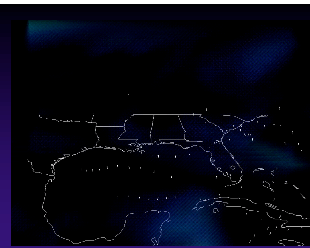
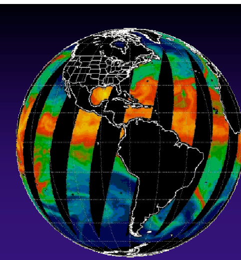






On the use of the high-resolution NASA/NCAR finite-volume General Circulation model for climate simulation, 10-day weather prediction, and a potential home land security application

S.-J. Lin

Data Assimilation Office

NASA Goddard Space Flight Center

Applications of fvGCM

- NASA's <u>operational</u> GEOS-4 Data Assimilation System
- Real-time 10-day weather forecasts (e.g., hurricane/typhoon track and snowstorm predictions)
- High-resolution climate experiments
- *NASA mission support* (*e.g.*, Shuttle re-entry incidence investigation; high-altitude U-2 flight planning)
- *Home land security (to be proposed)*

The NASa/nCAR fvGCM

The "FV" Dynamics:

- *Horizontal discretization: Flux-Form Semi-Lagrangian, conservative & monotonic*
- *Vertical discretization: Mass, momentum, and total energy conserving Lagrangian control-volume discretization*

CCM3 parameterizations with the following modifications and enhancements:

- *Large-scale ice-phase moist physics; re-evaporation of convective rain*
- *A simple prognostic O3 chemistry; source/sink of H2O in upper stratosphere*
- *Tuned components: cloud scheme; orographic and middle-atmosphere GWD*
- *Optional components: GSFC turbulence/PBL+RAS+Radiations; NCEP SAS*

Common Land Model (clm2) with extensive GSFC scientific and computational modifications and with high-resolution datasets (Boston University and MODIS)

3D primitive equations for the general vertical coordinate $\square$:

Mass conservation:

$$\frac{\partial}{\partial t}\square + \square \cdot \left(\vec{V}\square\right) = 0$$

Pseudo density $\square$:

$$\square = \frac{\partial p}{\partial \square} = \square\frac{\partial \square}{\partial \square}\square$$

Thermodynamic equation:

$$\frac{\partial}{\partial t}\left(\square\square\right) + \square \cdot \left(\vec{V}\square\square\right) = 0$$

Momentum equations:

$$\frac{\partial}{\partial t}u = \square v \square \frac{1}{A\cos\square}\left[\frac{\partial}{\partial \square}(\square + \square) + \frac{1}{\square}\frac{\partial}{\partial \square}p\right]\square\&\frac{\partial u}{\partial \square}$$

$$\frac{\partial}{\partial t}v = \square\square u \square \frac{1}{A}\left[\frac{\partial}{\partial \square}(\square + \square) + \frac{1}{\square}\frac{\partial}{\partial \square}p\right]\square\&\frac{\partial v}{\partial \square}$$

2D equations with the Lagrangian Control-Volume discretization:

Mass conservation:

$$\frac{\partial}{\partial t}\delta p+\nabla_h\cdot\left(\vec{V}\delta p\right)=0$$

$$\boxed{\pi=\frac{\partial p}{\partial \zeta}\;\rightarrow\;\delta p=\pi\delta\zeta}$$

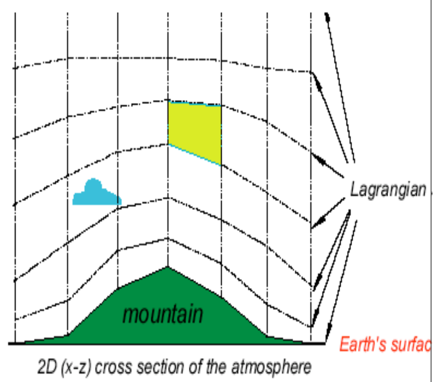
Thermodynamic equation:

$$\frac{\partial}{\partial t}\left(\Theta\delta p\right)+\nabla_h\cdot\left(\vec{V}\Theta\delta p\right)=0$$

Momentum equations:

$$\frac{\partial}{\partial t}u=\Omega v-\frac{1}{A\cos\theta}\left[\frac{\partial}{\partial\lambda}\left(\kappa+\Phi\right)+\underline{\frac{1}{\rho}\frac{\partial}{\partial\lambda}p}\right]$$

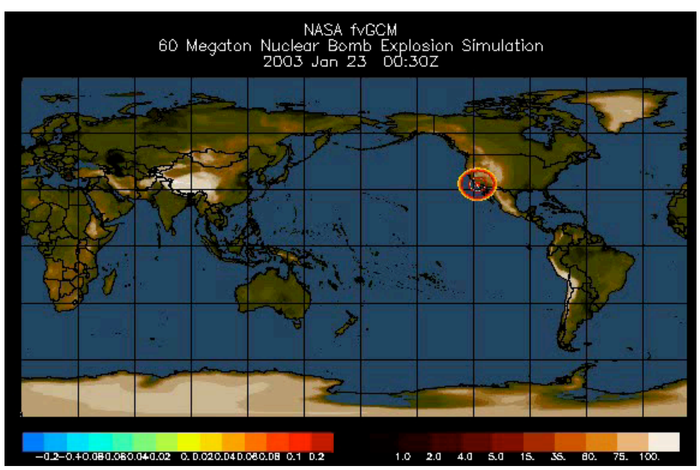
$$\frac{\partial}{\partial t}v=-\Omega u-\frac{1}{A}\left[\frac{\partial}{\partial\theta}\left(\kappa+\Phi\right)+\underline{\frac{1}{\rho}\frac{\partial}{\partial\theta}p}\right]$$

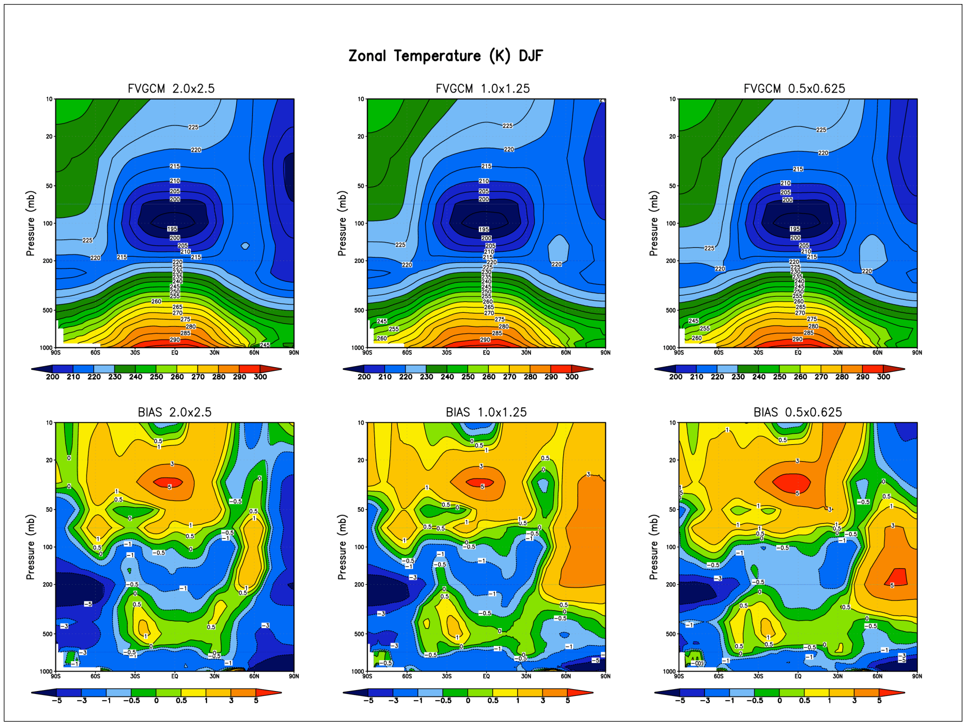


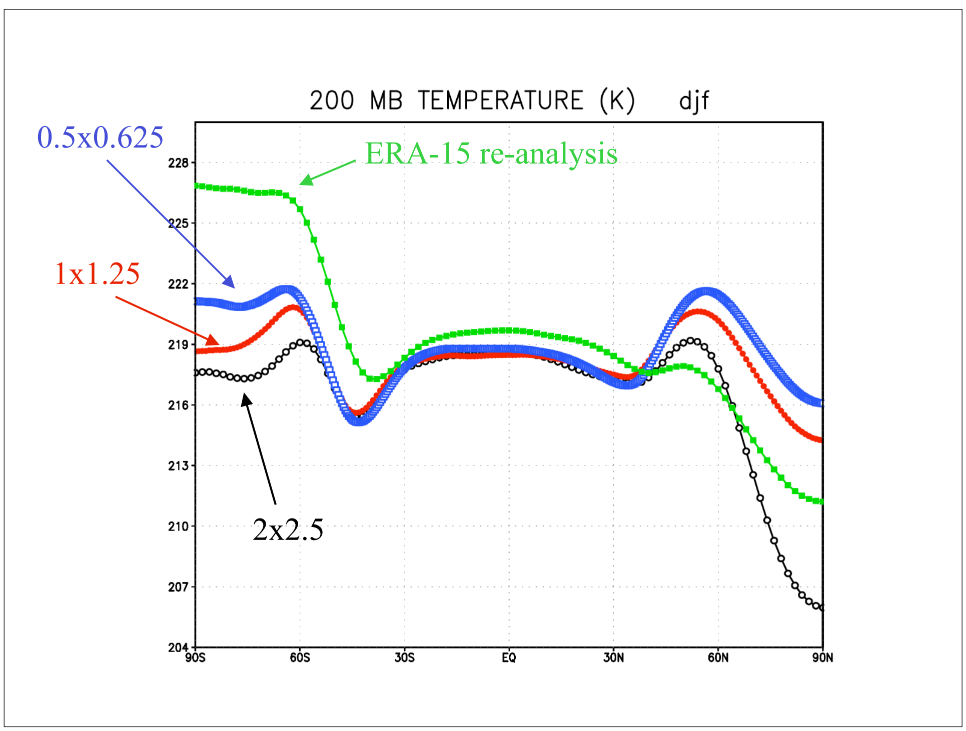
The "H-bomb test" of the model:

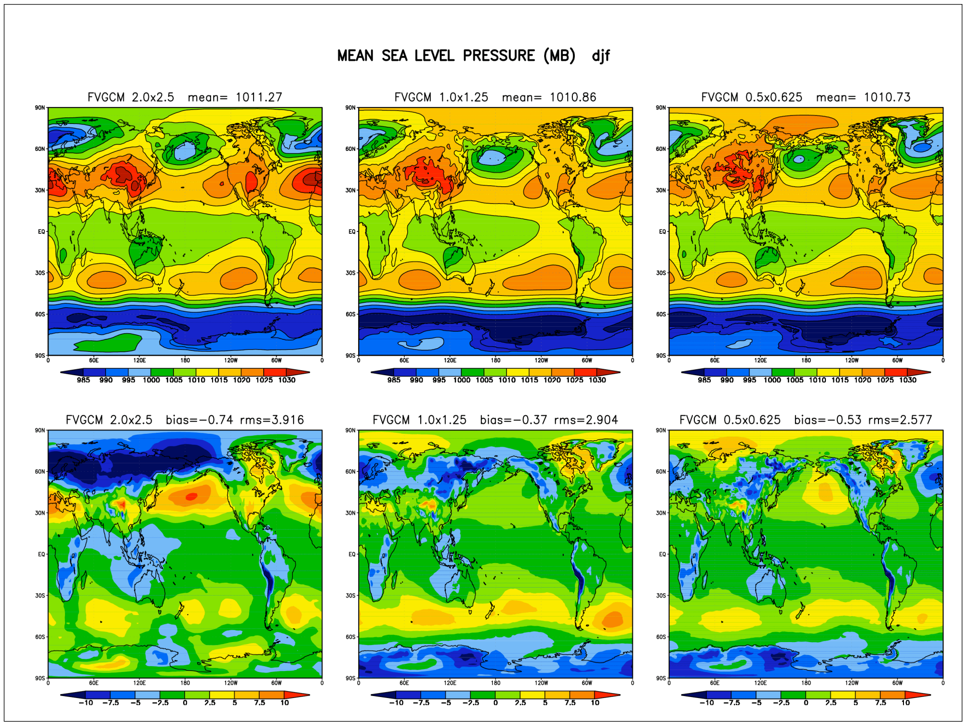
A hypothetical 60 megaton H-bomb over LA

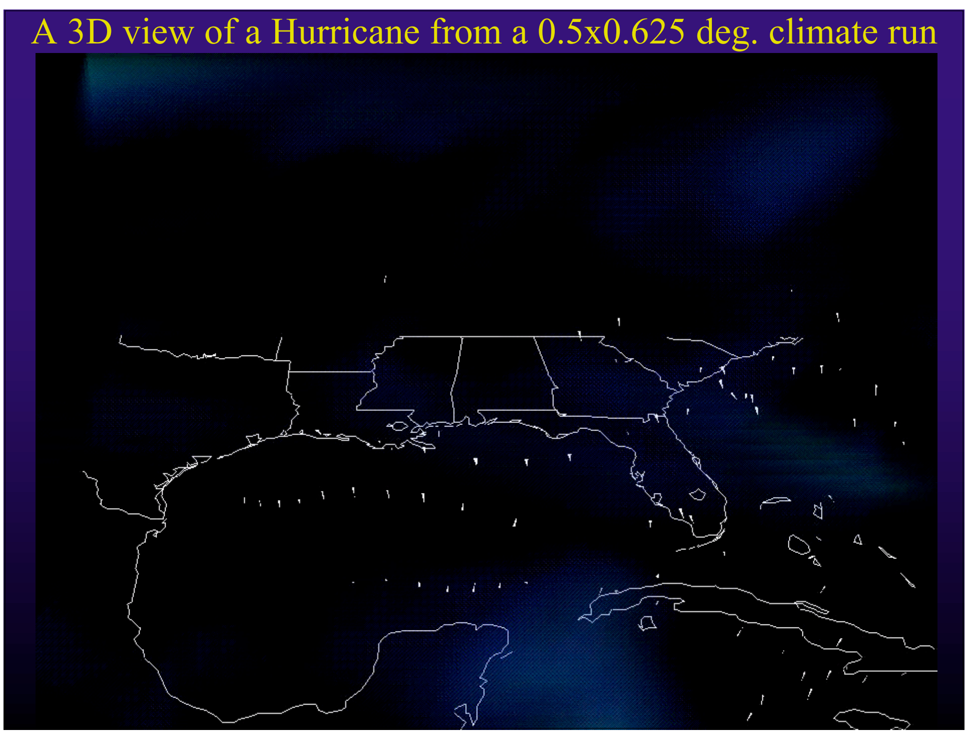
Assuming total energy E instantly, at t=0, converted to heat within a column below 500 mb: $E=C_p\Delta T\cdot Mass$




Zonal Temperature (K) DJF
FVGCM 2.0x2.5
FVGCM 1.0x1.25
FVGCM 0.5x0.625
BIAS 2.0x2.5
BIAS 1.0x1.25
BIAS 0.5x0.625
Pressure (mb)

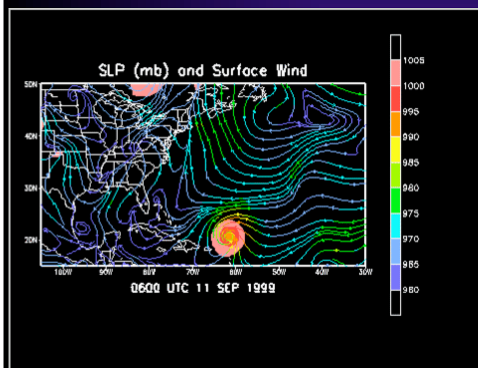

200 MB TEMPERATURE (K) djf
0.5x0.625
ERA-15 re-analysis
1x1.25
2x2.5
228
225
222
219
216
213
210
207
204
90S
60S
30S
EQ
30N
60N
90N


MEAN SEA LEVEL PRESSURE (MB) djf
FVGCM 2.0x2.5 mean= 1011.27
FVGCM 1.0x1.25 mean= 1010.86
FVGCM 0.5x0.625 mean= 1010.73
FVGCM 2.0x2.5 bias=-0.74 rms=3.916
FVGCM 1.0x1.25 bias=-0.37 rms=2.904
FVGCM 0.5x0.625 bias=-0.53 rms=2.577

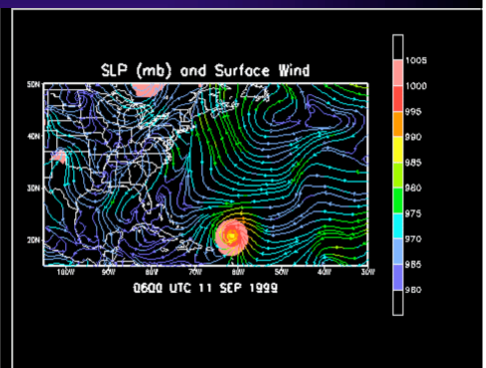

A 3D view of a Hurricane from a 0.5x0.625 deg. climate run

Assimilation & Prediction of Hurricane Floyd

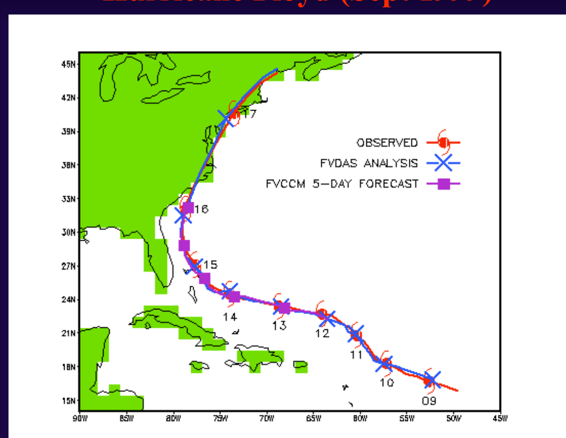
GEOS-4 analysis



fvGCM prediction



fvGCM assimilation and track forecast of Hurricane Floyd (Sept 1999)



Hurricane Floyd tracks from National Hurricane Center observed best track, NASA DAO Finite Volume Data Assimilation System (FVDAS) $1^\circ \times 1.25^\circ$ analysis, and FVCCM model 5-day forecast starting at 0000 UTC 12 September 1999.

Daily "Data flow"

Real-time 10-day Global Weather Predictions

NASA
Data Assimilation Office

Atmospheric state, SST, and Sea Ice data
After 4 AM

Before 8 AM
Global forecasts data at 55 km resolution

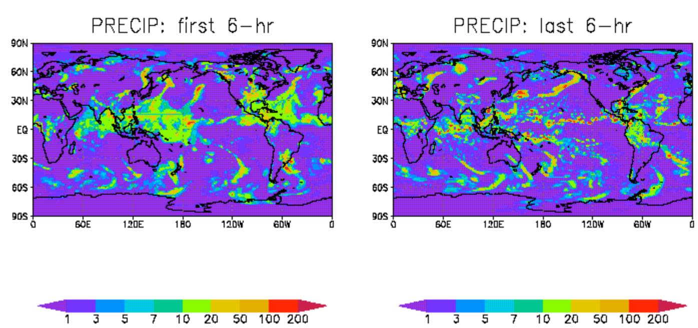
NOAA
National Centers for Environment Prediction

Daily 10-day forecast animations available to the public:

http://polar.gsfc.nasa.gov/sci_research/fvdas/NASCAR_web/nwp/

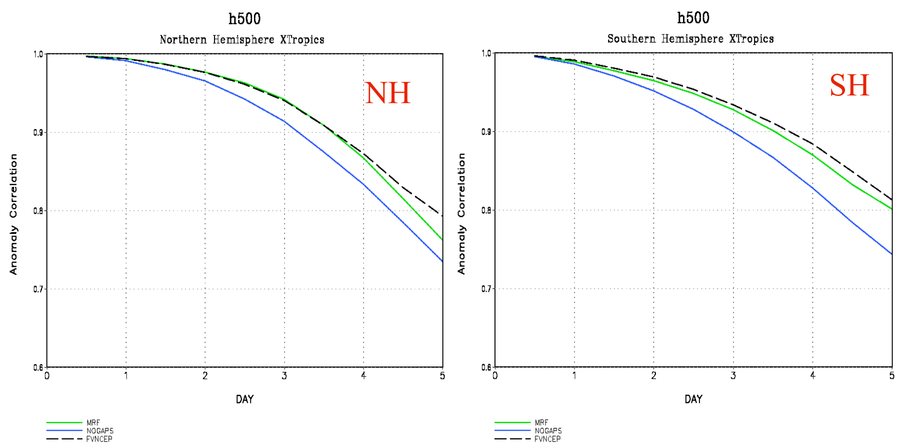
Example of the initial excessive precipitation:

7-day forecast from 00z Sept 19, 2002

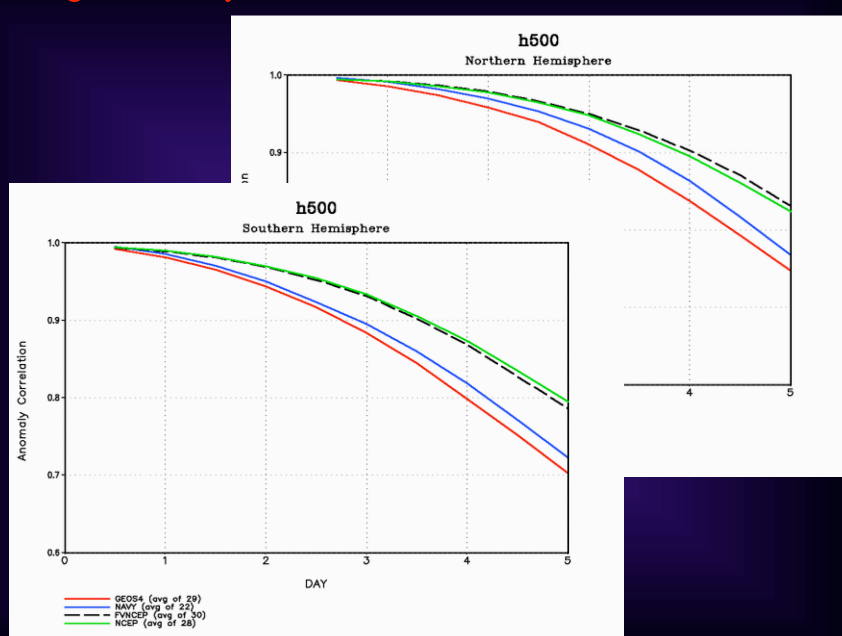


Anomaly Correlation for

Apr 22- May 12, 2002



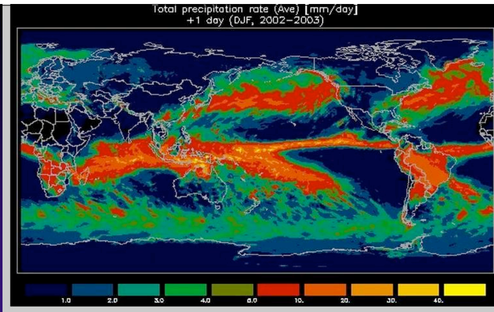
Averaged Anomaly Correlation Coefficient: Dec 2002



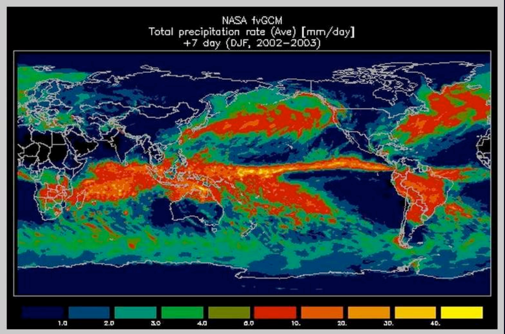
Average instant precip at 00Z

(averaged over DJF 2002-2003)

+ 1 day forecast



+7 days forecast



Average temperature biases

+ 1-Day forecast bias

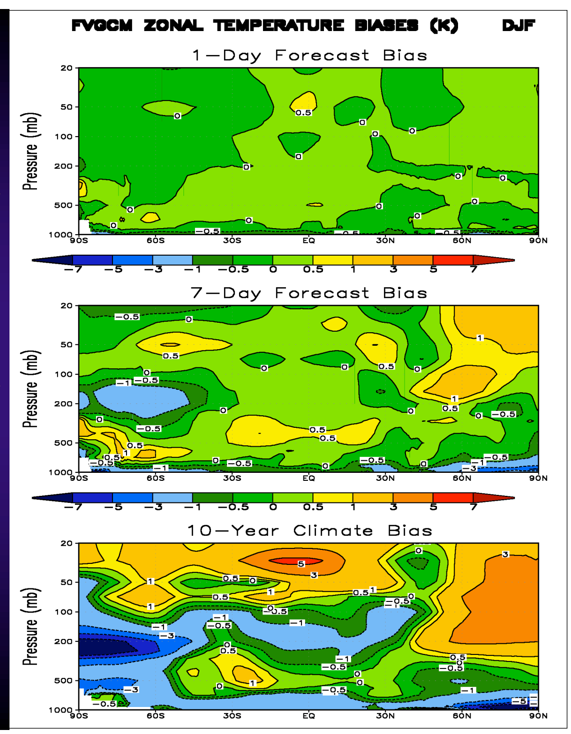
(DJF 2002-2003)

+ 7-Day forecast bias

(DJF 2002-2003)

Bias from a 10-yr

climate run

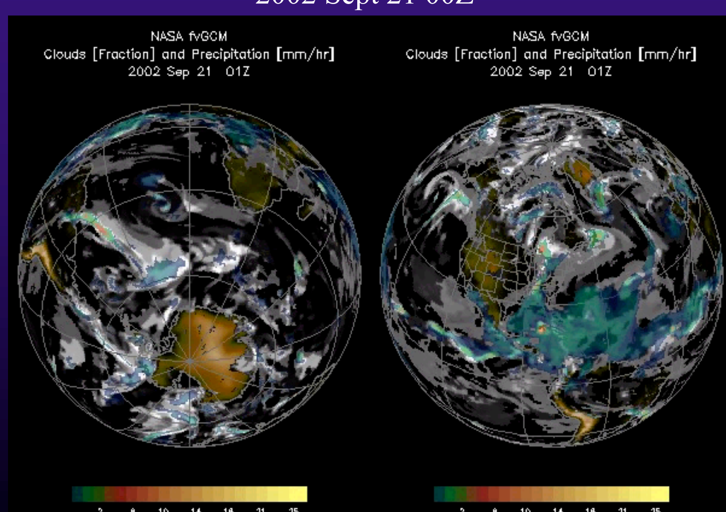


Tuning for "NWP" or "Climate"?

- Numerous tuning experiments have been performed, in both "weather prediction" and "climate" modes.
- "Tuning" in physics impacted very little the NWP skill up to day-5. Same tuning, however, can produce significant changes in climate.
- Wholesale swapping of physics packages or land models impacted NWP skill more significantly.
- Switching to the "2nd order scheme" in the "dynamics" degraded the forecast skill. But climate *appears* to be less sensitive to the same change.
- However, for NWP, by far the most sensitive change is the <u>Initial Condition</u> from different analysis systems.

NASA fvGCM Applications - *<u>Weather</u>*

Example of a 10-day forecast: *precipitation* and *clouds*
2002 Sept 21 00Z



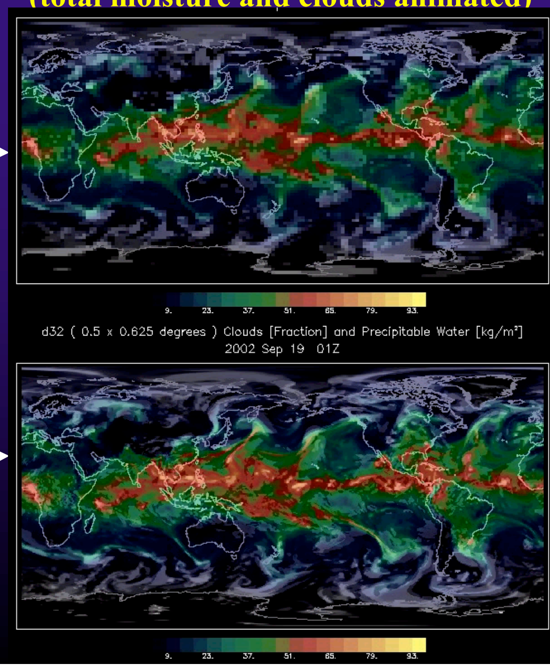
10-day Weather Predictions (*low vs. high resolution*)
(total moisture and clouds animated)

Prediction at 2° lat x 2.5° lon Resolution

10-day Forecast Initialized 00Z Sept. 19, 2002

Prediction at 0.5° lat x 0.625° lon Resolution

Column Moisture and Clouds



Why high resolution?

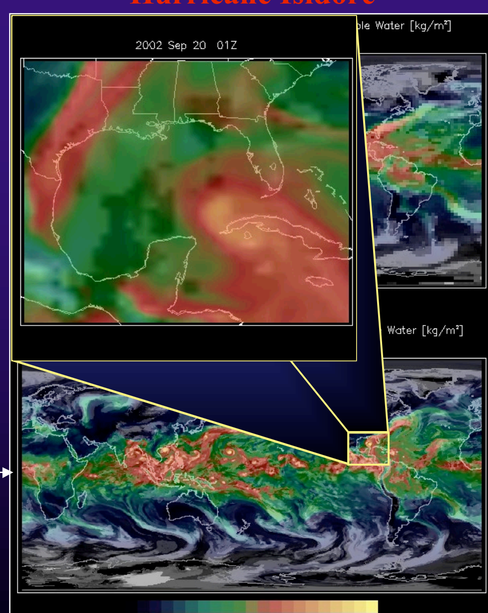
- Major weather events such as tropical hurricanes become resolvable
- Extra-tropical weather patterns become more clearly defined
- 3 hurricanes (Isidore, Lili, and Kyle) and 2 typhoons (Higos and Mekkhala) predicted during the 10-day period

Hurricane Isidore

Model Generated Moisture and Clouds

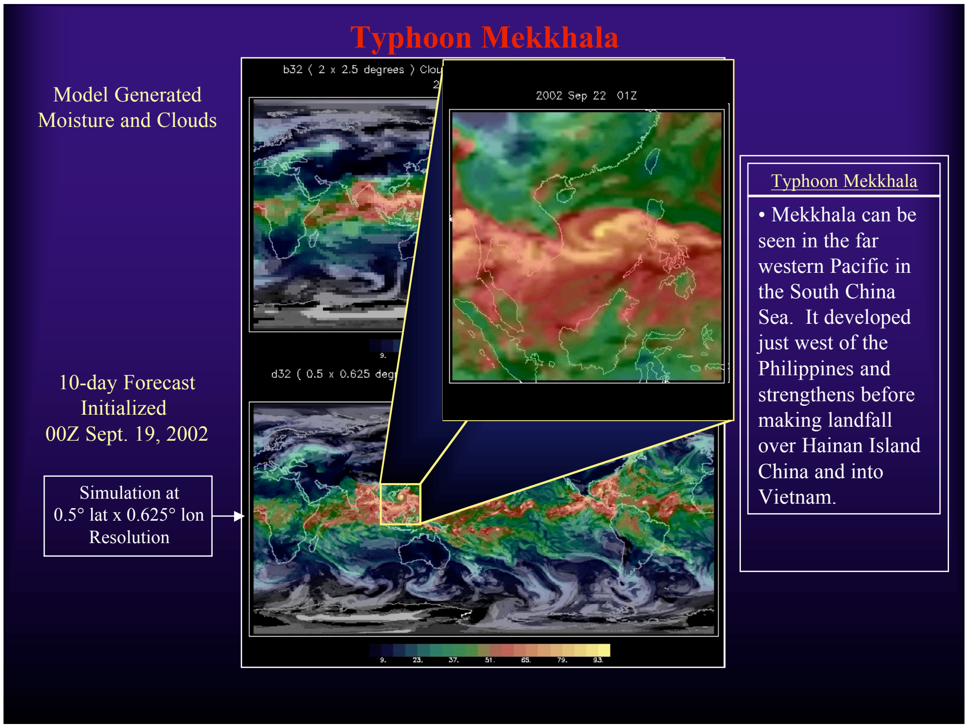
10-day Forecast Initialized 00Z Sept. 19, 2002

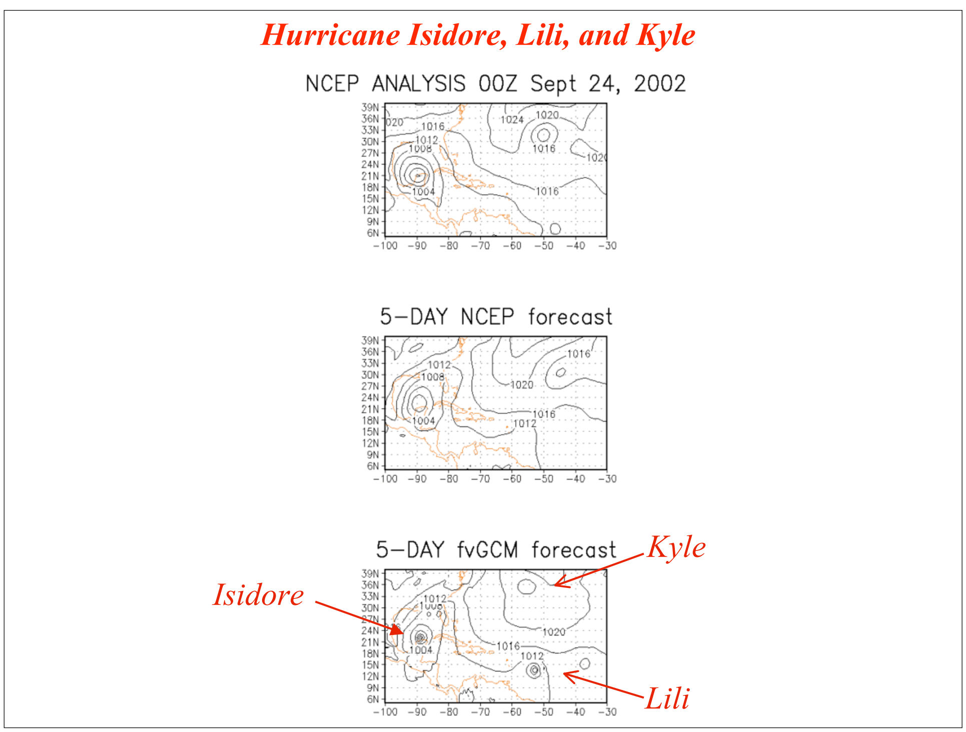
Simulation at 0.5° lat x 0.625° lon Resolution



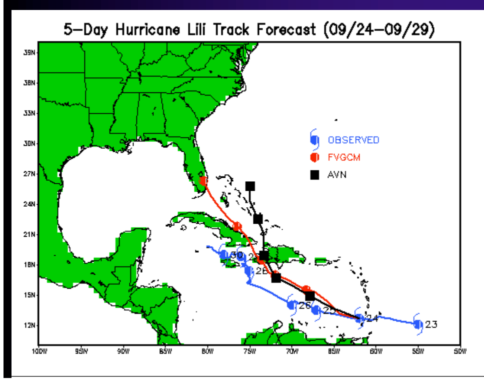
Hurricane Isidore

- Isidore developed in the western Caribbean during the first days of the time period and circled near the Yucatan before moving northward through the Gulf of Mexico and eventually making landfall over Louisiana.

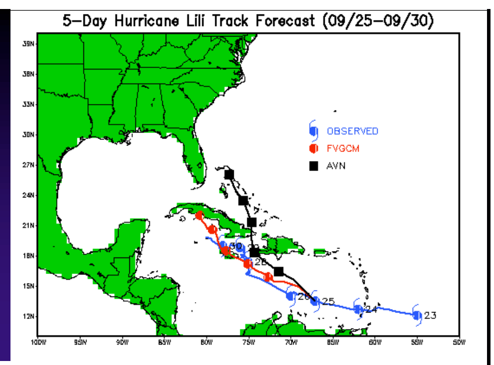

Typhoon Mekkhala
Model Generated Moisture and Clouds
10-day Forecast Initialized 00Z Sept. 19, 2002
Simulation at 0.5° lat x 0.625° lon Resolution
2002 Sep 22 01Z
Typhoon Mekkhala
• Mekkhala can be seen in the far western Pacific in the South China Sea. It developed just west of the Philippines and strengthens before making landfall over Hainan Island China and into Vietnam.

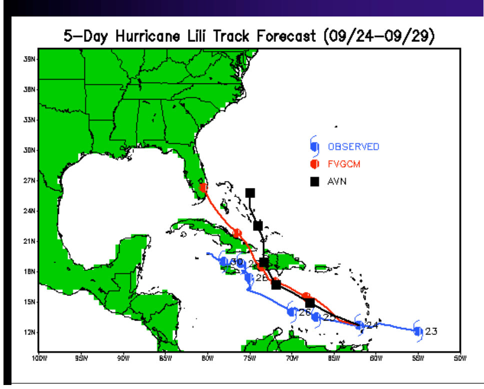

Hurricane Isidore, Lili, and Kyle
NCEP ANALYSIS 00Z Sept 24, 2002
5–DAY NCEP forecast
5–DAY fvGCM forecast
Isidore
Kyle
Lili

Track validation:
Hurricane Lili

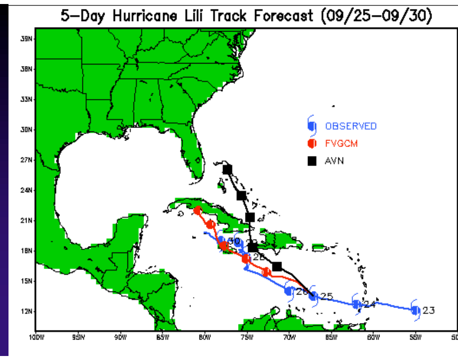


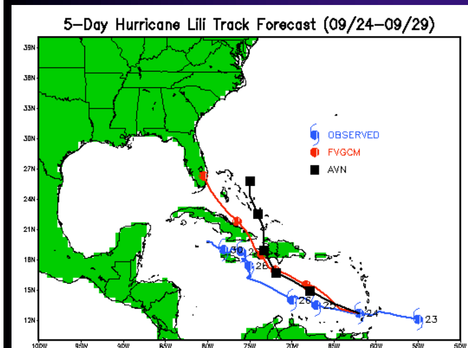
Track validation:
Hurricane Lili

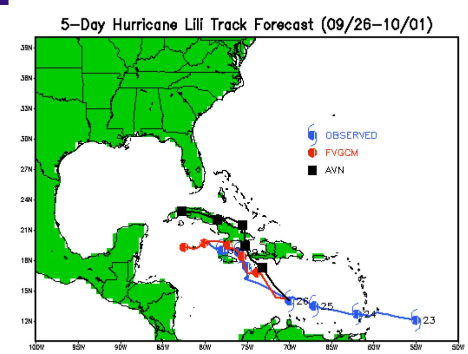




Track validation: Hurricane Lili







Independent validation of Prediction

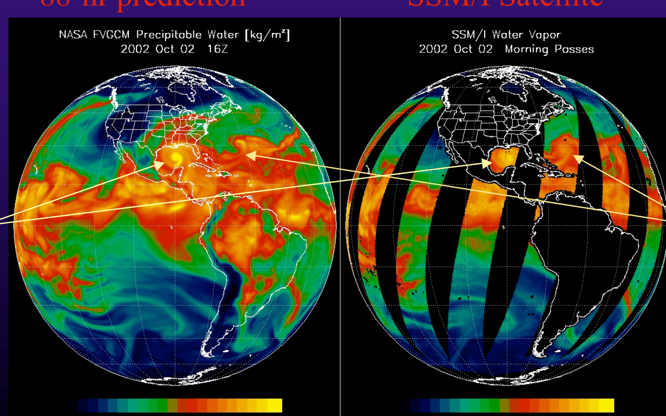
Atmospheric water vapor:

NASA fvGCM prediction *vs.* SSM/I Satellite

Initialized : 00Z 09-29-2002
Valid time: 16Z 10-02-2002

88-hr prediction | SSM/I Satellite

Hurricane Lili



Hurricane Kyle

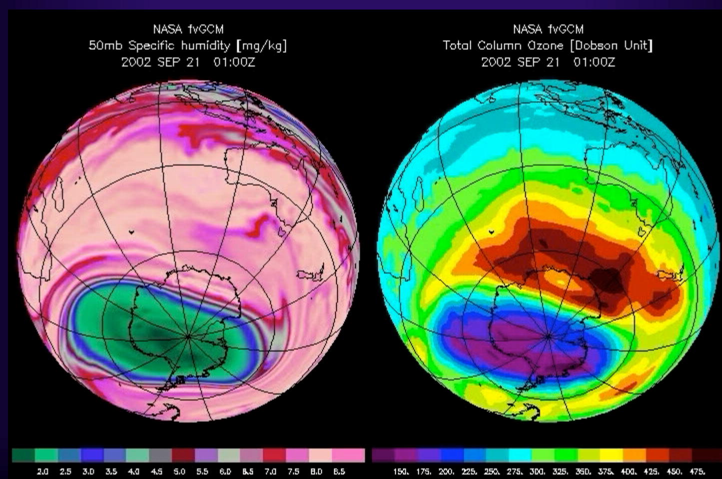
[SSM/I data are produced by Remote Sensing Systems and sponsored by the NASA Pathfinder Program for early Earth Observing System (EOS) products]

Prediction of the splitting of the Antarctica ozone-hole

(Sep 21 – Oct 1, 2002)

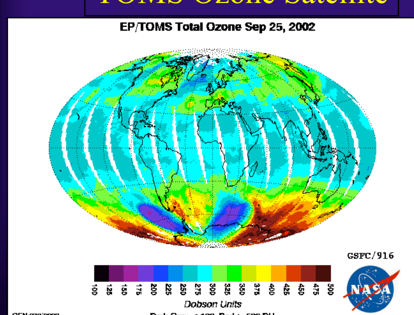
Specific Humidity @ 50 mb

Total Ozone (DU)

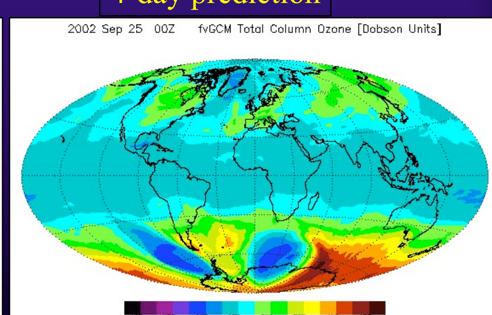


Validation of Ozone Prediction

TOMS Ozone Satellite

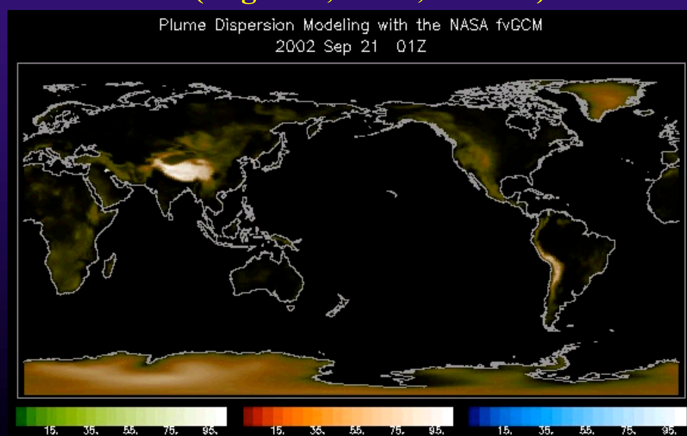


4-day prediction



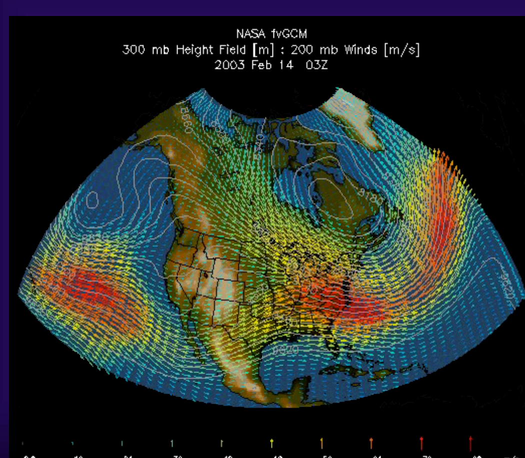
Home Land Security application

Experimental prediction **of the global transport of *radioactive gases* from 3 hypothetical "nuclear" explosions (Baghdad, Seoul, and LA)**



300 mb Height and 200 mb Winds

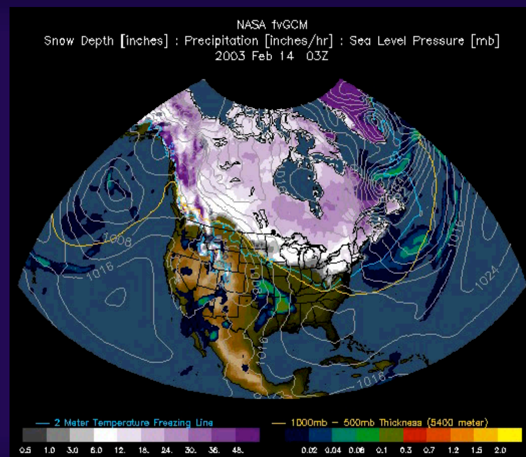
10-Day forecast from 00Z Feb 14,2003



The new "storm of the century" for the northeast US

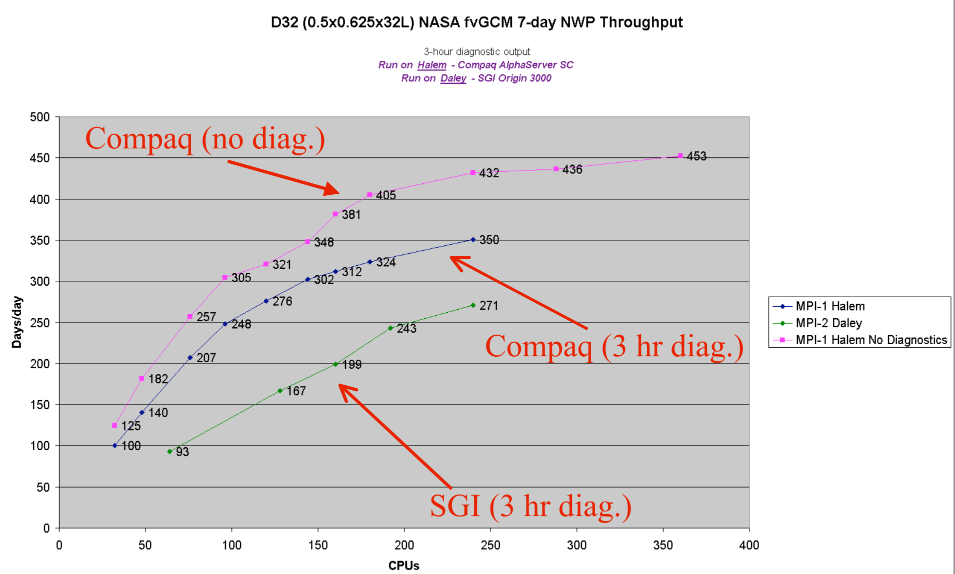
Snow Accumulation, SLP, and Precip Rate

10-Day forecast from 00Z Feb 14,2003



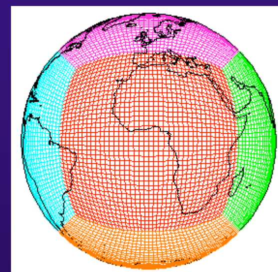
The new "storm of the century" for the northeast US

Throughput of the NWP configuration



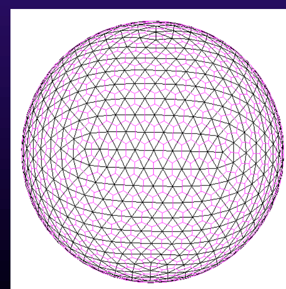
Possible future generations of FV dynamics

2nd generation ***hydrostatic*** finite-volume dynamical core on the "Cubed grid" for ***10-30 km*** resolution – <u>scalable to thousands of CPUs</u>.



3rd generation ***non-hydrostatic*** finite-volume dynamical cores on "spring-dynamics adjusted" Geodesic grid

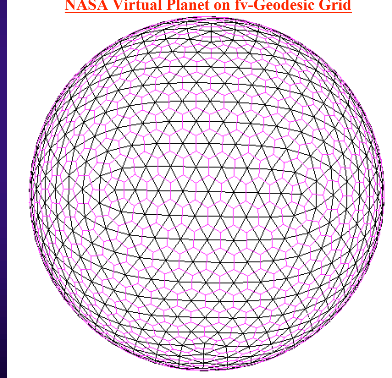
- High-order finite-volume algorithm
- Horizontal resolution of 5 km or finer capable of resolving clouds and gravity waves.
- Massively parallel with hybrid MPI-OpenMP <u>capable of scaling to over 40,000 CPUs</u>



The NASA Planet Simulator (2013?)

- Cumulus parameterization-free "cloud microphysics"
- High-order finite-volume (fv) non-hydrostatic dynamics
- Gravity-wave & cloud resolving resolution (5 km or finer)
- Model top at or above the mesopause (80 km)
- Scalable to over 40,000 CPUs
- Coupled to an eddy resolving ocean model
- Coupled to a dynamic sea ice model
- Coupled to a ultra-high-resolution land model
- Coupled to a full chemistry with 50 plus species

NASA Virtual Planet on fv-Geodesic Grid



- Enabling the assimilation of NASA and NOAA high-resolution satellite data

Final Remarks:

- The best tuning for "mean climate" is usually the best for NWP!
- *Relative* (*vs*. NCEP) forecast skills show strong seasonal dependency; fvGCM performs *relatively* better during *winter-spring time and relatively poorer for summer and early fall.*
- NASA fvGCM excels in small-scale storms and fronts -- producing sharp-gradient and relatively noise-free flows.
- Initialization technique, particularly for land and clouds, needs improvement.
- "Mega pixel" horizontal resolution (~ 25 km) to be "operational" in NWP mode by late 2003.
- A global cloud and gravity-wave resolving model for the "NASA planet simulator" by 2013?